

# On the determination of $\Theta^+$ quantum numbers and other topics of exotic baryons

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## 1 Introduction

In this talk I look into three different topics, addressing first a method to determine the quantum numbers of the  $\Theta^+$ , then exploiting the possibility that the  $\Theta^+$  is a bound state of  $K\pi N$  and in the third place I present results on a new resonant exotic baryonic state which appears as dynamically generated by the Weinberg Tomozawa  $\Delta K$  interaction.

## 2 Determining the $\Theta^+$ quantum numbers through the $K^+p \rightarrow \pi^+ K^+ n$

A recent experiment by LEPS collaboration at SPring-8/Osaka [1] has found a clear signal for an  $S = +1$  positive charge resonance around 1540 MeV. The finding, also confirmed by DIANA at ITEP [2], CLAS at Jefferson Lab. [3] and SAPHIR at ELSA [4] and other more recent experiments, might correspond to the exotic state predicted by Diakonov *et al.* in Ref. [5], but since then much theoretical work has been done to understand the nature of this resonance, see [6] for a recent review of theoretical and experimental work done. Yet, the spin, parity and isospin are not determined experimentally. We present here one particularly suited reaction to determine the quantum numbers with the process

$$K^+p \rightarrow \pi^+ K^+ n . \quad (1)$$

A successful model for the reaction (1) was considered in Ref. [7], consisting of the mechanisms depicted in terms of Feynman diagrams in Fig. 1. The term (a) (pion pole) and (b) (contact term), which are easily obtained from the chiral Lagrangians involving meson-meson [8] and meson-baryon

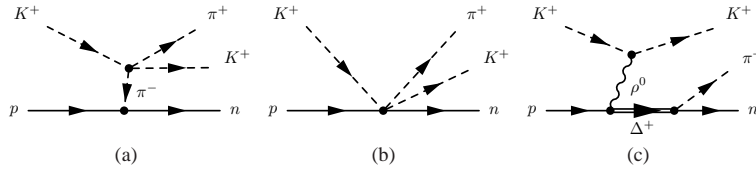


Figure 1: Feynman diagrams of the reaction  $K^+p \rightarrow \pi^+ K^+ n$  in the model of Ref. [7].

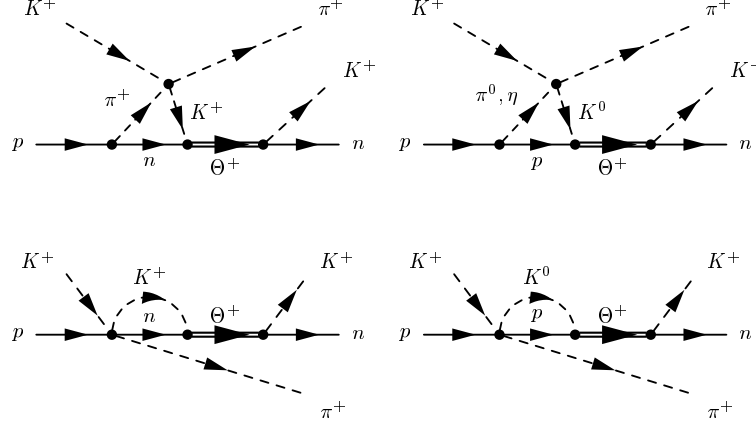


Figure 2: Feynman diagrams of the reaction  $K^+p \rightarrow \pi^+ K^+ n$  with the  $\Theta^+$  resonance.

interaction [9] are spin flip terms (proportional to  $\boldsymbol{\sigma}$ ), while the  $\rho$  exchange term (diagram (c)) contains both a spin flip and a non spin flip part. Having an amplitude proportional to  $\boldsymbol{\sigma}$  is important in the present context in order to have a test of the parity of the resonance. Hence we choose a situation, with the final pion momentum  $\mathbf{p}_{\pi^+}$  small compared to the momentum of the initial kaon, such that the diagram (c), which contains the  $\mathbf{S} \cdot \mathbf{p}_{\pi^+}$  operator can be safely neglected. The terms of Fig. 1 (a) and (b) will provide the bulk for this reaction. If there is a resonant state for  $K^+n$  then this will be seen in the final state interaction of this system. This means that in addition to the diagrams (a) and (b) of Fig. 1, we shall have those in Fig. 2. If the resonance is an  $s$ -wave  $K^+n$  resonance then  $J^P = 1/2^-$ . If it is a  $p$ -wave resonance, we can have  $J^P = 1/2^+, 3/2^+$ . A straightforward evaluation of the meson pole and contact terms (see also Ref. [10]) leads to the  $K^+n \rightarrow \pi^+ K N$  amplitudes

$$-it_i = (a_i + b_i \mathbf{k}_{in} \cdot \mathbf{q}' + c_i) \boldsymbol{\sigma} \cdot \mathbf{k}_{in} + (-a_i - b_i \mathbf{k}_{in} \cdot \mathbf{q}' + d_i) \boldsymbol{\sigma} \cdot \mathbf{q}' , \quad (2)$$

where  $i = 1, 2$  stands for the final state  $K^+n, K^0p$  respectively and  $k_{in}$  and  $q'$  are the initial and final  $K^+$  momenta. The coefficients  $a_i$  and  $b_i$  are from meson exchange terms, and  $c_i$  and  $d_i$  from contact terms. They are given in Ref. [11]. When taking into account  $KN$  scattering through the  $\Theta^+$  resonance, as depicted in Fig. 2, the  $K^+p \rightarrow \pi^+ K^+ n$  amplitude is given by

$$-i\tilde{t} = -it_1 - i\tilde{t}_1 - i\tilde{t}_2 \quad (3)$$

where  $\tilde{t}_1$  and  $\tilde{t}_2$  account for the scattering terms with intermediate  $K^+n$  and  $K^0p$ , respectively. They

are given by

$$\begin{aligned}
-\tilde{t}_i^{(s)} &= \frac{g_{K^+n}^2}{M_I - M_R + i\Gamma/2} \left\{ G(M_I)(a_i + c_i) - \frac{1}{3}\bar{G}(M_I)b_i \right\} \boldsymbol{\sigma} \cdot \mathbf{k}_{in} S_I(i) , \\
-\tilde{t}_i^{(p,1/2)} &= \frac{\bar{g}_{K^+n}^2}{M_I - M_R + i\Gamma/2} \bar{G}(M_I) \left\{ \frac{1}{3}b_i \mathbf{k}_{in}^2 - a_i + d_i \right\} \boldsymbol{\sigma} \cdot \mathbf{q}' S_I(i) , \\
-\tilde{t}_i^{(p,3/2)} &= \frac{\bar{g}_{K^+n}^2}{M_I - M_R + i\Gamma/2} \bar{G}(M_I) \frac{1}{3}b_i \left\{ (\mathbf{k}_{in} \cdot \mathbf{q}')(\boldsymbol{\sigma} \cdot \mathbf{k}_{in}) - \frac{1}{3}\mathbf{k}_{in}^2 \boldsymbol{\sigma} \cdot \mathbf{q}' \right\} S_I(i) ,
\end{aligned} \tag{4}$$

for  $s$ - and  $p$ -wave, and  $i = 1, 2$  for  $K^+n$  and  $K^0p$  respectively. The different magnitudes of Eqs. (4) are defined in [11], but the only thing to recall here is the dependence on the momenta of the  $\boldsymbol{\sigma} \cdot \mathbf{p}$  terms. Invariant mass distributions and angular distributions are given in [11]. Here we only want to discuss the polarization observables.

Let us now see what can one learn with resorting to polarization measurements. Eqs. (4) account for the resonance contribution to the process. The interesting finding there is that if the  $\Theta^+$  couples to  $K^+n$  in  $s$ -wave (hence negative parity) the amplitude goes as  $\boldsymbol{\sigma} \cdot \mathbf{k}_{in}$ , while if it couples in  $p$ -wave it has a term  $\boldsymbol{\sigma} \cdot \mathbf{q}'$ . Hence, a possible polarization test to determine which one of the couplings the resonances chooses is to measure the cross section for initial proton polarization  $1/2$  in the direction  $z$  ( $\mathbf{k}_{in}$ ) and final neutron polarization  $-1/2$  (the experiment can be equally done with  $K^0p$  in the final state, which makes the nucleon detection easier). In this spin flip amplitude  $\langle -1/2 | t | +1/2 \rangle$ , the  $\boldsymbol{\sigma} \cdot \mathbf{k}_{in}$  term vanishes. With this test the resonance signal disappears for the  $s$ -wave case, while the  $\boldsymbol{\sigma} \cdot \mathbf{q}'$  operator of the  $p$ -wave case would have a finite matrix element proportional to  $q' \sin \theta$ . This means, away from the forward direction of the final kaon, the appearance of a resonant peak in the cross section would indicate a  $p$ -wave coupling and hence a positive parity resonance.

In Fig. 3 we show the results for the polarized cross section measured at 90 degrees as a function of the invariant mass. The two cases with  $s$ -wave do not show any resonant shape since only the background contributes. All the other cross sections are quite reduced to the point that the only sizeable resonant peak comes from the  $I, J^P = 0, 1/2^+$  case. A clear experimental signal of the resonance in this observable would unequivocally indicate the quantum numbers as  $I, J^P = 0, 1/2^+$ .

### 3 Is the $\Theta^+$ a $K\pi N$ bound state?

At a time when many low energy baryonic resonances are being dynamically generated as meson baryon quasibound states within chiral unitary approaches [12, 13, 14, 15, 16, 17] it looks tempting to investigate the possibility of this state being a quasibound state of a meson and a baryon or two mesons and a baryon. Its nature as a  $KN$   $s$ -wave state is easily ruled out since the interaction is repulsive.  $KN$  in a  $p$ -wave, which is attractive, is too weak to bind. The next logical possibility is to consider a quasibound state of  $K\pi N$ , which in  $s$ -wave would naturally correspond to spin-parity  $1/2^+$ , the quantum numbers suggested in [5]. Such an idea has already been put forward in [18] where a study of the interaction of the three body system is conducted in the context of chiral

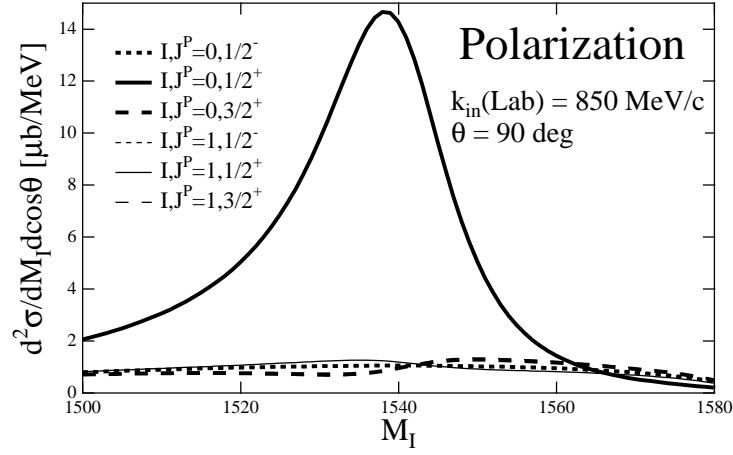


Figure 3: The double differential cross sections of polarized amplitude with  $\theta = 90$  for  $I = 0, 1$  and  $J^P = 1/2^-, 1/2^+, 3/2^+$ .

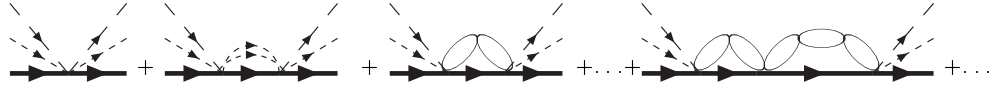


Figure 4: Diagrams considered in the  $\kappa N$  interaction.

quark models, which suggests that it is not easy to bind the system although one cannot rule it out completely. A more detailed work is done in [19], which we summarize here.

Upon considering the possible structure of  $\Theta^+$  we are guided by the experimental observation [3] that the state is not produced in the  $K^+p$  final state. This would rule out the possibility of the  $\Theta$  state having isospin  $I=1$ . Then we accept the  $\Theta^+$  to be an  $I=0$  state. As we couple a pion and a kaon to the nucleon to form such state, a consequence is that the  $K\pi$  substate must combine to  $I=1/2$  and not  $I=3/2$ . This is also welcome dynamically since the s-wave  $K\pi$  interaction in  $I=1/2$  is attractive (in  $I=3/2$  repulsive) [20]. The attractive interaction in  $I=1/2$  is very strong and gives rise to the dynamical generation of the scalar  $\kappa$  resonance around 850 MeV and with a large width [20].

One might next question that, with such a large width of the  $\kappa$ , the  $\Theta^+$  could not be so narrow as experimentally reported. However, this large  $\kappa$  width is no problem since in our scenario it would arise from  $K\pi$  decay, but now the  $K\pi N$  decay of the  $\Theta^+$  is forbidden as the  $\Theta^+$  mass is below the  $K\pi N$  threshold.

One might hesitate to call the possible theoretical  $\Theta^+$  state a  $\kappa N$  quasibound state because of the large gap of about 200 MeV to the nominal  $\kappa N$  mass. The name though is not relevant here and we can opt by calling it simply a  $K\pi N$  state, but the fact is that the  $K\pi$  system is strongly correlated even at these lower energies, and since this favours the binding of the  $K\pi N$  state we take it into account.

In order to determine the possible  $\Theta^+$  state we search for poles of the  $K\pi N \rightarrow K\pi N$  scattering matrix. To such point we construct the series of diagrams of fig. 4. where we account explicitly for the  $K\pi$  interaction by constructing correlated  $K\pi$  pairs and letting the intermediate  $K\pi$  and nucleon propagate. This requires a kernel for the two meson-nucleon interaction which we now address. We

formulate the meson-baryon lagrangian in terms of the SU(3) matrices,  $B$ ,  $\Gamma_\mu$ ,  $u_\mu$  and the implicit meson matrix  $\Phi$  standard in ChPT [9],

$$L = \text{Tr} (\bar{B} i \gamma^\mu \nabla_\mu B) - M_B \text{Tr} (\bar{B} B) + \frac{1}{2} D \text{Tr} (\bar{B} \gamma^\mu \gamma_5 \{u_\mu, B\}) + \frac{1}{2} F \text{Tr} (\bar{B} \gamma^\mu \gamma_5 [u_\mu, B]) \quad (5)$$

with the definitions in [9].

First there is a contact three body force simultaneously involving the pion, kaon and nucleon, which can be derived from the meson- baryon Lagrangian term containing the covariant derivative  $\nabla_\mu$ .

Next we show that a nucleon, kaon and pion see an attractive interaction in an isospin zero state through this contact potential. By taking the isospin  $I=1/2$   $\kappa$  states and combining them with the nucleon, also isospin  $1/2$ , we generate  $I=0,1$  states which diagonalize the scattering matrix associated to  $t_{mB}$

$$\begin{aligned} \langle \Theta^1 | t_{mB}^s | \Theta^1 \rangle &= -\frac{1}{144 f^4} (-4(K + K') - 11(\not{p} + \not{p}')) \\ \langle \Theta^0 | t_{mB}^s | \Theta^0 \rangle &= -\frac{21}{144 f^4} ((K + K') - (\not{p} + \not{p}')) \end{aligned} \quad (6)$$

The usual non-relativistic approximation  $\bar{u} \gamma^\mu k_\mu u = k^0$  is applied. Since the  $K\pi N$  system is bound by about 30 MeV one can take for a first test  $k^0$ ,  $p^0$  as the masses of the  $K$  and  $\pi$  respectively and one sees that the interaction in the  $I=0$  channel is attractive, while in the  $I=1$  channel is repulsive. This would give chances to the  $\kappa N$   $t$ -matrix to develop a pole in the bound region, but rules out the  $I=1$  state.

The series of terms of Fig. 4 might lead to a bound state of  $\kappa N$  which would not decay since the only intermediate channel is made out of  $K\pi N$  with mass above the available energy. The decay into  $KN$  observed experimentally can be taken into account by explicitly allowing for an intermediate state provided by diagrams including  $K\pi \rightarrow K\pi$  with the  $\pi$  being absorbed by the nucleon in p-wave, which leads to  $K\pi N \rightarrow KN$ . This and other diagrams accounting for the interaction of the mesons with the other meson or the nucleon are taken into account in the calculations [19].

What we find at the end is that, in spite of the attraction found, this interaction is not enough to bind the system, since we do not find a pole below the  $K\pi N$  threshold. In order to quantify this second statement we increase artificially the potential  $t_{mB}$  by adding to it a quantity which leads to a pole around  $\sqrt{s} = 1540 \text{ MeV}$  with a width of around  $\Gamma = 40 \text{ MeV}$ . This is accomplished by adding an attractive potential around five or six times bigger than the existing one. This exercise gives a quantitative idea of how far one is from having a pole. We should however note that we have not exhausted all possible sources of three body interaction since only those tied to the Weinberg Tomozawa term have been considered. We think that some more work in this direction should be still encouraged and there are already some steps given in [21].

## 4 A resonant $\Delta K$ state as a dynamically generated exotic baryon

Given the success of the chiral unitary approach in generating dynamically low energy resonances, one might wonder if other resonances could not be produced with different building blocks than those used normally, the octets of stable baryons and the pseudoscalar mesons. In this sense, in [22] the interaction of the decuplet of  $3/2^+$  with the octet of pseudoscalar mesons is shown to lead to many states that have been associated to experimentally well established resonances. The purpose of the present work is to show that this interaction leads also to a new state of positive strangeness, with  $I = 1$  and  $J^P = 3/2^-$ , hence, an exotic baryon which qualifies as a pentaquark in the quark language, but which is more naturally described in terms of a resonant state of a  $\Delta$  and a  $K$ .

The lowest order chiral Lagrangian for the interaction of the baryon decuplet with the octet of pseudoscalar mesons is given by [23]

$$\mathcal{L} = i\bar{T}^\mu \not{D} T_\mu - m_T \bar{T}^\mu T_\mu \quad (7)$$

where  $T_{abc}^\mu$  is the spin decuplet field and  $D^\nu$  the covariant derivative given by in [23].

Let us recall the identification of the  $SU(3)$  component of  $T$  to the physical states :  $T^{111} = \Delta^{++}$ ,  $T^{112} = \frac{1}{\sqrt{3}}\Delta^+$ ,  $T^{122} = \frac{1}{\sqrt{3}}\Delta^0$ ,  $T^{222} = \Delta^-$ ,  $T^{113} = \frac{1}{\sqrt{3}}\Sigma^{*+}$ ,  $T^{123} = \frac{1}{\sqrt{6}}\Sigma^{*0}$ ,  $T^{223} = \frac{1}{\sqrt{3}}\Sigma^{*-}$ ,  $T^{133} = \frac{1}{\sqrt{3}}\Xi^{*0}$ ,  $T^{233} = \frac{1}{\sqrt{3}}\Xi^{*-}$ ,  $T^{333} = \Omega^-$ .

For strangeness  $S = 1$  and charge  $Q = 3$  there is only one channel  $\Delta^{++}K^+$  which has  $I = 2$ . For  $S = 1$  and  $Q = 2$  there are two channels  $\Delta^{++}K^0$  and  $\Delta^+K^+$ . From these one can extract the transition amplitudes for the  $I = 2$  and  $I = 1$  combinations and we find [24]

$$V(S = 1, I = 2) = \frac{3}{4f^2}(k^0 + k'^0); \quad V(S = 1, I = 1) = -\frac{1}{4f^2}(k^0 + k'^0), \quad (8)$$

where  $k(k')$  indicate the incoming (outgoing) meson momenta. These results indicate that the interaction in the  $I = 2$  channel is repulsive while it is attractive in  $I = 1$ . This attractive potential and the physical situation is very similar to the one of the  $\bar{K}N$  system in  $I = 0$ , where the interaction is also attractive and leads to the generation of the  $\Lambda(1405)$  resonance [12, 13, 14, 15]. The use of  $V$  as the kernel of the Bethe Salpeter equation [13], or the N/D unitary approach of [14] both lead to the scattering amplitude

$$t = (1 - VG)^{-1}V \quad (9)$$

In eq. (9),  $V$  factorizes on shell [13, 14] and  $G$  stands for the loop function of the meson and baryon propagators, the expressions for which are given in [13] for a cut off regularization and in [14] for dimensional regularization.

Next we fix the scale of regularization by determining the cut off,  $q_{max}$ , in the loop function of the meson and baryon propagators in order to reproduce the resonances for other strangeness and isospin channels. They are one resonance in  $(I, S) = (0, -3)$ , another one in  $(I, S) = (1/2, -2)$  and another one in  $(I, S) = (1, -1)$ . The last two appear in [22] around 1800 MeV and 1600 MeV and

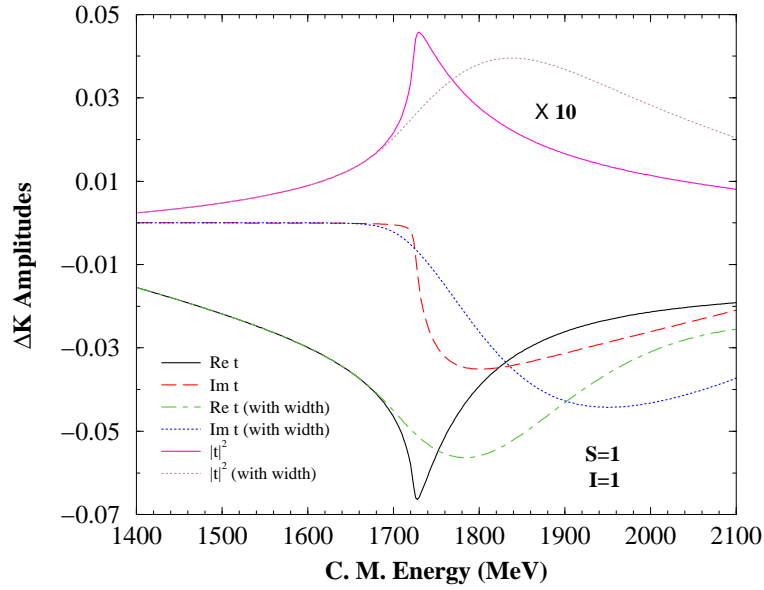


Figure 5: Amplitudes for  $\Delta K \rightarrow \Delta K$  for  $I = 1$

they are identified with the  $\Xi(1820)$  and  $\Sigma(1670)$ . We obtain the same results as in [22] using a cut off  $q_{max} = 700$  MeV.

With this cut off we explore the analytical properties of the amplitude for  $S = 1$ ,  $I = 1$  in the first and second Riemann sheets. First we see that there is no pole in the first Riemann sheet. However, if we increase the cut off to 1.5 GeV we find a pole below threshold corresponding to a  $\Delta K$  bound state. But this cut off does not reproduce the position of the resonances discussed above.

Next we explore the second Riemann sheet for which we take

$$G^{2nd} = G + 2i \frac{p_{CM}}{\sqrt{s}} \frac{M}{4\pi} \quad (10)$$

where  $G$  is the meson baryon propagator and the variables on the right hand side of the equation are evaluated in the first (physical) Riemann sheet. In the above equation  $p_{CM}$ ,  $M$  and  $\sqrt{s}$  denote the CM momentum, the  $\Delta$  mass and the CM energy respectively. We find a pole at  $\sqrt{s} = 1635$  MeV in the second Riemann sheet. This should have some repercussion on the physical amplitude and indeed this is the case as we show below.

The situation in the scattering matrix is revealed in figs. 5 and 6 which show the real and imaginary part of the  $K\Delta$  amplitudes for the case of  $I = 1$  and  $I = 2$  respectively. Using the cut off discussed above we can observe the differences between  $I = 1$  and  $I = 2$ . For the case of  $I = 2$  the imaginary part follows the ordinary behaviour of the opening of a threshold, growing smoothly from threshold. The real part is also smooth, showing nevertheless the cusp at threshold. For the case of  $I = 1$ , instead, the strength of the imaginary part is stuck to threshold as a reminder of the existing pole in the complex plane, growing very fast with energy close to threshold. The real part has also a pronounced cusp at threshold, which is also tied to the same singularity.

We have also done a more realistic calculation taking into account the width of the  $\Delta$  in the intermediate states. The results are also shown in figures 5 and 6 and we see that the peaks around threshold become smoother and some strength is moved to higher energies. Even then, the strength

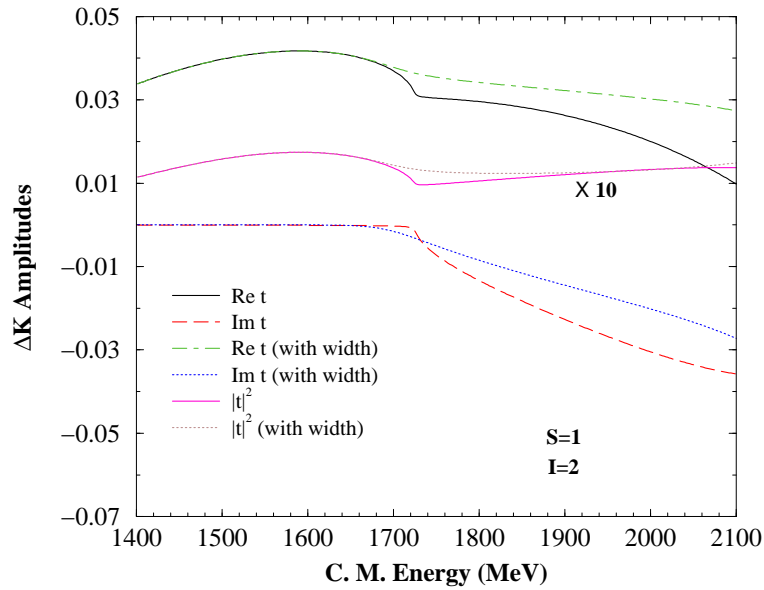


Figure 6: Amplitudes for  $\Delta K \rightarrow \Delta K$  for  $I = 2$

of the real and imaginary parts in the  $I = 1$  are much larger than for  $I = 2$ . The modulus squared of the amplitudes shows some peak behavior around 1800 MeV in the case of  $I = 1$ , while it is small and has no structure in the case of  $I = 2$ .

We propose the study of the following reactions: 1)  $pp \rightarrow \Lambda \Delta^+ K^+$ , 2)  $pp \rightarrow \Sigma^- \Delta^{++} K^+$ , 3)  $pp \rightarrow \Sigma^0 \Delta^{++} K^0$ . In the first case the  $\Delta^+ K^+$  state produced has necessarily  $I = 1$ . In the second case the  $\Delta^{++} K^+$  state has  $I = 2$ . In the third case the  $\Delta^{++} K^0$  state has mostly an  $I = 1$  component. The study of these reactions, particularly the invariant mass distribution of  $\Delta K$ , and the comparison of the  $I = 1$  and  $I = 2$  cases would provide the information we are searching for. Indeed, the mass distribution is given by

$$\frac{d\sigma}{dm_{I(\Delta K)}} = C |t_{\Delta K \rightarrow \Delta K}|^2 p_{CM} \quad (11)$$

where  $p_{CM}$  is the  $K$  momentum in the  $\Delta K$  rest frame. The mass distribution removing the  $p_{CM}$  factor in eq. (11) should show the broad peak of  $|t_{\Delta K \rightarrow \Delta K}|^2$  seen in fig. 5. Similarly, the ratio of mass distributions in the cases 3) to 2) or 1) to 2), discussed before, should show this behaviour.

Given the success of the chiral unitary approach providing dynamically generated resonances in the interaction of the octet of  $1/2^+$  baryons with the octet of pseudoscalar mesons, as well as in the scalar sector of the meson meson interaction [25], the predictions made here stand on firm ground. The experimental confirmation of the results found here would give evidence for another pentaquark state which, however, stands for a simple description as a resonant  $\Delta K$  state.

## 5 Acknowledgments

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